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FINAL REPORT

On

NASA GRANT NSG-05-020-223

for

COLLABORATIVE RESEARCH  
IN CARDIOVASCULAR DYNAMICS  
AND BONE ELASTICITY

(NASA-CR-140997) COLLABORATIVE RESEARCH  
IN CARDIOVASCULAR DYNAMICS AND BONE  
ELASTICITY Final Report (Stanford Univ.)  
14 p HC \$3.25 CSCL 06P

N75-12572

63/52 02852

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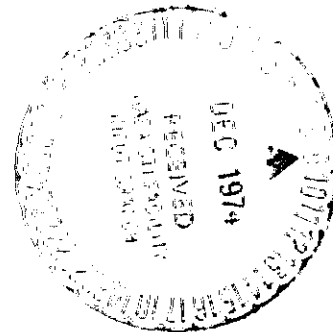
National Aeronautics and Space Administration

by the

Department of Aeronautics and Astronautics

Stanford University  
Stanford, California

October 1974



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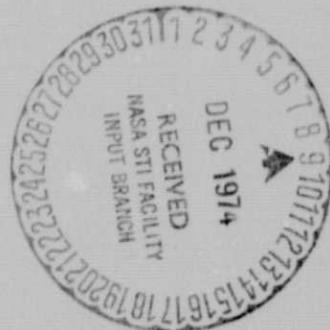
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## GENERAL REVIEW

Under Grant No. NGR/L 05-020-223 the Ames Center of the NASA and Stanford University were engaged in a collaborative research program covering a variety of topics of biomechanics and biomedical engineering within the fields of cardiovascular dynamics, respiration, bone elasticity and vestibular physiology. This cooperative effort has evolved from studies carried out by the principal investigator and Eric Ogden, M.D., Chief of the Environmental Biology Division at Ames, during the former's tenure as a Senior Postdoctoral Resident Research Associate from 1965 to 1967. Since Stanford University did not have the facilities required for interdisciplinary investigations in biomechanics and biomedical engineering, the studies supported by this grant and others were mainly performed within the Ames laboratories, and to this end the Stanford members of the cooperative team were extended guest worker privileges by the Ames Center. The research accomplishments and stimulation that have been generated by this limited pooling of resources and efforts between Stanford University and Ames endorse the recommendation of closer ties between government laboratories and universities made by the Federal Council for Science and Technology\*. The goals of the research supported by Grant No. NGR/L 05-020-223 were

1. a better understanding of the mechanical behavior of the circulatory system and its control mechanisms.
2. Development of noninvasive methods of measuring the changes in the mechanical properties of blood vessels and other cardiovascular parameters in man.

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\* See "Federal Labs: White House Study Urges Closer University Ties, "Science, Vol.159, pp. 412-414, January 26, 1968; also "Education and the Federal Laboratories. An assessment of Federal laboratory educational activities and their present and potential relationship with universities". Report published by the Federal Council for Science and Technology, Committee on Federal Laboratories, March 1968.

3. Application of these noninvasive methods to examine in man the physiological effects of environmental changes, including earth-simulated gravitational changes.
4. Development of in-flight methods for studying the events which lead to post-flight postural hypotension.

Progress made towards these goals had been described in a series of progress-reports and also in 26 full-length publications, 28 short publications, 20 PhD Dissertations and 2 Engineer's theses listed in Appendix I, II and III.

With the appointment of the principal investigator as Professor of Biomedical Engineering at the University of Zurich and Swiss Federal Institute of Technology, Zurich, in October 1971 some of the work, PhD-students and staff were transferred to Switzerland. Thanks to several favorable circumstances including a) the financial support given by the Swiss Federal Government and the Department of Education of the Canton Zurich, b) the loan of NASA laboratory equipment, and c) the close collaboration between the clinical departments of the medical school of the University of Zurich and the Institute of Biomedical Engineering, the projects started under the NASA Grants could be expanded and the human aspects of the research goals much better pursued. As a result of the interdisciplinary efforts in Zurich, we have now in clinical use several prototypes of pulsed ultrasound velocity profile meters which enable us to quantify non-invasively the blood flow in larger arteries and veins of patients with circulatory disorders. Besides this, a new method for measuring changes in the mineral content and cross-section of appendicular bones is now being utilized in the pediatric hospital of the University of Zurich in conjunction with a pilot study of the effects of various therapeutic procedures (including bedrest and inactivity) on calcium metabolism. All data and

information on the research and development work carried out as a continuation of the former Ames projects are available to NASA.

On behalf of Stanford University, the University of Zurich, the Swiss Federal Institute of Technology in Zurich and the students and faculty associated with the projects supported by NASA Grant NGR/L 05-020-223 I wish to express our sincere thanks for the opportunity to partake in NASA's research and development programs.

A final budgetary statement on Grant NGR/L 05-020-223 is given in Appendix IV.



## APPENDIX I

### FULL-LENGTH PUBLICATIONS

1. "The Dispersion of Waves in Blood Vessels" (co-author J.A. Maxwell), Biomechanics, Proceedings of a Symposium Sponsored by the Applied Mechanics Division of the ASME, November 30. (editor J.C. Fung), pp 47-67 (1966)
2. "An Example of Maximum Energy Dissipation in Slow Viscous Flow" (E.Y. Harper and I.D. Chang), J. Fluid Mech. Vol. 33, pt 2, pp 209-225 (1968)
3. "The Dissipation and Dispersion of Small Waves in Arteries and Veins with Viscoelastic Wall Properties" (co-author J. Maxwell), Biophysical Journal, Vol. 8, pp 920-950 (1968)
4. "Transmission Characteristics of Axial Waves in Blood Vessels" (co-authors W. Moritz and E. Ogden), Journal of Biomechanics, Vol. 1, No. 4, pp 235-246 (1968)
5. "Dispersion and Attenuation of Small Artificial Pressure Waves in the Canine Aorta" (co-authors M. Hirst and E. Ogden), Circulation Research, Vol. XXIII, October, pp 539-551 (1968)
6. "Model Studies of Retinal Settling Under Various Dynamic Forces" (co-authors D.T. Hayashi and J. Silvis), Archives of Ophthalmology, Vol. 81, January, pp 58-62 (1969)
7. "The Transmission Characteristics of Large and Small Pressure Waves in the Abdominal Vena Cava" (co-authors M. Wells and E. Ogden), IEEE Transactions on Biomedical Engineering, Vol. BME-16, No. 4, October, pp 262-273 (1969)
8. "Theoretical Analysis of Nonlinear Phenomena Affecting the Pressure and Flow Pulse in Arteries" (co-authors R.L. Rockwell and E. Ogden), Proceedings of Specialists' Meeting on Fluid Dynamics of Blood Circulation and Respiratory Flow, May 4-6, Naples, Italy, (AGARD Conference Proceedings No. 65), pp 22-1 - 22-10 (1970)
9. "Mathematical Models for the Mechanical Behavior of Intact Bones" (co-authors M. Farshad and D.R. Young), Proceedings of Bone Measurement Conference, May 22-23, Chicago, Illinois, pp 79-114 (1970)
10. "Determination of Mechanical Properties of Excised Dog Radii from Lateral Vibration Experiments" (co-authors G.A. Thompson and D.R. Young), Proceedings of Bone Measurement Conference, May, 22-23, Chicago, Illinois, pp 115-137 (1970)

11. "Theoretical Model Studies of Wave Transmission in Semicircular Canal Ducts" (co-author M. Dorfman), Ingenieur-Archiv, Vol. 39, No. 6, October, pp 390-406 (1970)
12. "The Role of Perilymph in the Response of Semicircular Canals" (co-author W.C. Van Buskirk), Proceedings of Fifth Symposium on the Role of the Vestibular Organs in Space Exploration, Pensacola, Florida, August 19-21 (1970)
13. "Experimental Model Studies of Some Dynamic Response Characteristics of the Semicircular Canals" (co-author W.C. Van Buskirk), in "Dynamical Response of Biomechanical Systems", ed. N. Perrone, ASME Monograph, pp 101-132 (1970)
14. "Possible Hemodynamic Phenomena Involved in the Genesis of Atherosclerosis", Advances in Experimental Medicine and Biology: Proceedings of a Conference on Fundamental Data on Reactions of Vascular Tissue in Man, Lindau, West Germany, April 19-25, 1970, New York, Plenum Press (1971)
15. "Biomechanical Studies in Aerospace Physiology" (co-author J. Billingham), IEEE Spectrum, Vol. 8, No. 3, March, pp 64-72 (1971)
16. "Nonlinear Analysis of Flow Pulses and Shock Waves in Arteries. Part I: Derivation and Properties of Mathematical Model. Part II: Parametric Study Related to Clinical Problems" (co-authors R.L. Rockwell and E. Ogden), Zeitschrift für Angewandte Mathematik und Physik, Vol. 22, pp 217-246 and 563-581 (1971)
17. "The Role of Perilymph in the Response of the Semicircular Canals to Angular Acceleration" (co-author W.C. Van Buskirk), Acta Otolaryngologica, Vol. 72, pp 93-100 (1971)
18. "Toward a Nontraumatic Study of the Circulatory System", in Biomechanics - its Foundations and Objectives (eds. Y.C. Fung, N. Perrone), Prentice Hall, New Jersey, pp. 337-379 (1971)
19. "Transmission of Small Pressure Waves in the Canine Vena Cava" (co-authors W.G. Yates and E. Ogden), American Journal of Physiology, Vol. 221, No. 2, August, pp 644-651 (1971)
20. "Ocular Vibration in Relation to Retinal Settling" (co-authors D.T. Hayashi, G. Brom Walsh, H. Portwood and H.A. Leon), Annals of Ophthalmology, September 3, pp 994-1000 (1971)
21. "Effects of Viscosity and Constraints on the Dispersion and Dissipation of Waves in Large Blood Vessels, I. Theoretical Analysis" (co-authors E. Jones and I.D. Chang), Biophysical Journal, Vol. 11, pp 1085-1120 (1971)



22. "Effects of Viscosity and Constraints on the Dispersion and Dissipation of Waves in Large Blood Vessels, II. Comparison of Analysis with Experiments" (co-authors E. Jones and I.D. Chang), Biophysical Journal, Vol. 11, pp 1121-1134 (1971)
23. "A Laser Study of the Motion of Particles Suspended in a Slow Viscous Shear Flow" (R.S. Chadwick and I.D. Chang) J. of Colloid and Interface Science, Vol. 42, No. 3, pp 516-534, March (1973)
24. "Influence of Flow and Pressure on Wave Propagation in the Canine Aorta" (co-author M. Hirstand), Circulation Research, Vol. 32, April, pp 524-529 (1973)
25. "Active and Passive Behavior of the Canine Vena Cava in Vivo" (co-author W.G. Yates), American Journal of Physiology, Vol. 227, No. 1, July, pp 24-30 (1974)
26. "Wave Transmission Characteristics and Anisotropy of Canine Carotid Arteries" (co-author W.E. Moritz), Journal of Biomechanics, Vol. 7, pp 151-154 (1974)

## APPENDIX II

### SHORT PUBLICATIONS

1. "Transmission Velocity of Induced Pulse Waves in Arteries" (co-author L. Wolterink), Federation Proceedings, Vol. 25, p. 394 (1966)
2. "Effects of Various Drugs on the Transmission of Waves in the Vena Cava" (co-author E. Ogden), The Physiologist, Vol. 9, No. 3. August, p. 131 (1966)
3. "Elastic Properties of the Inferior Vena Cava Determined by Wave Transmission" (co-author E. Ogden) Circulation, Supplement III, Vols. XXIII and XXXIV, October, p. 44 (1966)
4. "Direct Measurement of Dissipation of Waves in Arteries and Veins" (co-authors M. Hirst, E. Ogden and R.M. Westbrook), Proceedings of the 19th Annual Conference on Engineering in Medicine and Biology, Vol. 8, p. 17 (1966)
5. "The Effects of Transmural Pressure on the Speed of Artificial Pulses in Veins" (co-authors E. Ogden and M. Wells), presented at the Fluid Mechanics Division Meeting of the American Physical Society, Nov. 21-23, 1966, Stanford University. Abstract in Bulletin of the American Physical Society, Series 2, Vol. 12, p. 832 (1967)
6. "The Distensibility of Dog Ventricles and their Response to Rapid Injections" (co-author E. Ogden), Federation Proceedings, Vol. 26, p. 718 (1967)
7. "Effects of Pressure on Dispersion and Attenuation of Waves in the Aorta" (co-author E. Ogden), Invited Paper, Digest of 7th International Conference on Medical and Biological Engineering, Stockholm, Sweden, August 14-19, p. 149 (1967)
8. "Intravascular Transmission Characteristics of Artificially Induced Heart Sounds" (co-author E. Ogden), Circulation Supplement II, Vol. XXXVI, No. 4, October, pp 254-255 (1967)
9. "The Dissipation and Dispersion of Waves in Large Arteries and Veins with Viscoelastic Wall Properties" (co-author J.A. Maxwell), Proceedings of the 20th Annual Conference on Engineering in Medicine and Biology, Boston, Massachusetts, November 13-16, p.6.1. (1967)
10. "New Techniques for the Study of the Elastic Behavior of the Heart and Large Arteries and Veins" (co-authors E. Ogden and W.J. Astleford), Invited Paper, Proceedings of the 20th Annual Conference on Engineering in Medicine and Biology, Boston, Massachusetts, November 13-16, p. 11.2 (1967)

11. "Effects of Pressure and Flow on the Transmission Properties of Small Sinusoidal Pressure Waves in the Aortae of Anesthetized Dogs" (co-authors M. B. Histan and E. Ogden), Proceedings of the XXIV International Congress of Physiological Sciences, Washington, D.C., Volunteer Abstract, No. 37, p. 13 (1968)
12. "In Vivo Studies of Axial Stiffness of Blood Vessels" (co-authors W. Moritz and E. Ogden), Proceedings of the XXIV International Congress of Physiological Sciences, Washington, D.C., Volunteer Abstract No. 38, p. 13 (1968)
13. "Variations of Distensibility of the Vena Cava of Anesthetized Dogs" (co-authors E. Ogden, M. Wells and W. Yates), Proceedings of the XXIV International Congress of Physiological Sciences, Washington, D.C., Volunteer Abstract No. 39, p.13 (1968)
14. "Changes in Waveform of Pressure Pulses in Arteries and Veins Due to the Pressure Dependence of the Wave Speed" (co-authors M. Wells and E. Ogden), Proceedings of the XXIV International Congress of Physiological Sciences, Washington, D.C., Volunteer Abstract No. 40, p. 14 (1968)
15. "Dispersions and Attenuation of Distension Waves in the Abdominal Vena Cava (co-authors M. Wells and E. Ogden), Proceedings of the 21st Annual Conference on Engineering in Medicine and Biology, Houston, Texas, November 18-21, p. 23.6 (1968)
16. "Effects of Viscosity and Constraints on Axial and Distension Waves in Blood Vessels" (co-authors E. Jones and I.D. Chang), Proceedings of the 21st Annual Conference on Engineering in Medicine and Biology, Houston, Texas, November 18-21, p.23.1 (1968)
17. "Spectra of Intravascular Heart Sounds: Their Generation and Transmission" (co-authors E. Ogden and W. Astleford), Federation Proceedings, Vol. 28, No. 2, April, p. 583 (1969)
18. "Indication for Anisotropic Wall Properties of the Carotid Artery in Living Dogs" (co-author W.E. Moritz), Proceedings of the 8th International Conference on Medical and Biological Engineering, Chicago, Illinois, July 19-25, p. 27.5 (1969)
19. "Shock Waves and other Nonlinear Phenomena of Wave Propagation in Blood Vessels" (co-author R.L. Rockwell), Proceedings of the 8th International Conference on Medical and Biological Engineering, Chicago, Illinois, July 19-25, p. 6.4 (1969)
20. "Nonlinear Effects of Pressure and Flow on the Transmission of Pressure Waves in the Canine Aorta" (co-author M.B. Histan), The Physiologist, Vol. 12, No. 3, August, p. 255 (1969)

21. "Physiologic Activity of the Canine Vena Cava" (co-authors E. Ogden and W. Yates), The Physiologist, Vol. 12, No. 3, August, p. 318 (1969)
22. "Parametric Analysis of Pressure and Flow Pulses in Arterial Conduits" (co-authors R.L. Rockwell and E. Ogden), The Physiologist, Vol. 13, August, p. 295 (1970)
23. "Active Responses of the Canine Vena Cava" (co-authors W.G. Yates and E. Ogden), Proceedings of the 23rd Annual Conference on Engineering in Medicine and Biology, Washington, D.C., November 15-19, Vol. 12, p. 251 (1970)
24. "A New Approach to the Measurement of Central Venous Pressure" (co-authors E. Ogden, M.K. Wells and H. Sandler), Proceedings of the XXV International Congress of Physiological Sciences, Munich, West Germany, p. 427, (1971)
25. "Experimental and Theoretical Studies of the Lung as an Elastic Structure" (co-authors W.R. Powell and J. Billingham), Proceedings of the XXV International Congress of Physiological Sciences, Munich, West Germany, p. 459 (1971)
26. "Mechanical Properties of Intact Bones" (co-authors M. Farshad, G. Thompson and D. Young), Digest of the 9th International Conference on Medical and Biological Engineering, Melbourne, Australia, p. 157, (1971)
27. "A Multiple Gate Pulse Doppler Flowmeter" (co-author F.D. McLeod), IEEE Ultrasonics Symposium, Miami Beach, Florida, December, p. 51 (1971)
28. "A Nonlinear Model of a Viscoelastic Arterial System" (co-author R.L. Rockwell), 3rd Annual Meeting of the Biomedical Engineering Society, Baltimore, Maryland, April 7 & 8, No. 75 (1972)



### APPENDIX III

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#### A. PH.D. DISSERTATIONS ASSOCIATED WITH NASA GRANT NGR/L 05-020-223

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|--|-------|------|
| 1. James A. Maxwell  | June  | 1967 |
| "The Dispersion and Dissipation of Waves<br>in Blood Vessels"  |       |      |
| 2. Everett Jones   | June  | 1968 |
| "Effects of Viscosity and External Con-<br>stants on Wave Transmission in Blood<br>Vessels"                            |       |      |
| 3. Merlin Dorfman  | Jan.  | 1969 |
| "Theoretical Model Studies of Wave Propa-<br>gation in the Semicircular Canals"  |       |      |
| 4. Michael B. Histan   | April | 1969 |
| "An Experimental Study of the Transmis-<br>sion Characteristics of Pressure Waves<br>in the Aorta"                     |       |      |
| 5. Michael K. Wells  | April | 1969 |
| "On the Determination of the Elastic Proper-<br>ties of Blood Vessels from their Wave<br>Transmission Characteristics" |       |      |
| 6. William E. Moritz   | June  | 1969 |
| "Transmission Characteristics of Disten-<br>sion, Torsion and Axial Waves in Arteries"                                 |       |      |
| 7. John A.H. Bailie  | June  | 1969 |
| "Theoretical Studies on High Frequency<br>Wave Propagation in Blood Vessels"   |       |      |
| 8. Robert L. Rockwell  | Jan.  | 1970 |
| "Nonlinear Analysis of Pressure- and<br>Shock Waves in Blood Vessels"  |       |      |
| 9. William G. Yates  | Jan.  | 1970 |
| "Experimental Studies of the Variations<br>in the Mechanical Properties of the<br>Canine Abdominal Vena Cava"          |       |      |



- |   |       |      |
|---|-------|------|
| 10. William C. Van Buskirk  | April | 1970 |
| "Experimental and Theoretical Model<br>Studies of Some Dynamic Response Characteristics of the Semicircular Canals" |       |      |
| 11. Po Kee Wong   | June  | 1970 |
| "Waves in Viscous Fluids, Elastic Solids,<br>and Viscoelastic Materials"  |       |      |
| 12. William Frank Bozich  | Sept. | 1970 |
| "Wave Propagation in Simple Nonhomogeneous Systems with a Transition Point"   |       |      |
| 13. Mehdi Farshad   | April | 1971 |
| "Mathematical Models for the Electromechanical Behavior of Intact Bones"  |       |      |
| 14. Richard S. Chadwick   | June  | 1971 |
| "Light Scattering from Blood Cells in a Shear Flow"   |       |      |
| 15. Fortunato Orti-Daras  | June  | 1971 |
| "Investigation of Wave Propagation in Curved Elastic Tube Filled with Viscous Fluid"                                |       |      |
| 16. William R. Powell   | June  | 1971 |
| "Experimental and Theoretical Studies of the Lung as an Elastic Structure"  |       |      |
| 17. Gerald A. Thompson  | Sept. | 1971 |
| "Experimental Studies of Lateral and Torsional Vibrations of Intact Dog Radii"                                      |       |      |
| 18. Phillip J. Bendick  | April | 1973 |
| ...."A Laser Doppler Study of Velocity Profiles in Oscillatory Flow"  |       |      |
| 19. Kirk J. Bundy   | Dec.  | 1974 |
| "Experimental Studies of the Anisotropy and Nonuniformity of Compact Bone from Human Femurs"                        |       |      |
| 20. Doran R. Klingler   | Dec.  | 1974 |
| "Techniques of Measuring the Propagation of Pressure Waves in the Microcirculation"                                 |       |      |

B. ENGINEER'S THESES ASSOCIATED WITH NASA GRANT NGR/L  
05-020-223

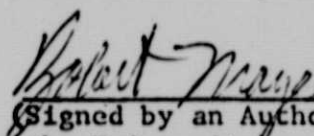
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1. William J. Astleford Dec. 1968  
"Direct Determination of Distensibility  
of the Left Ventricle of the Heart under  
In Vivo Conditions"
2. Li-Ko Chang June 1970  
"An Analytic Study of the Transmission of  
Pulse Wave in Tapered Vessels"

Grant No. NGR 05-020-223GRANTSFinal-Cumulative Cost Expenditure Report

1. Cumulative Award.....	562,486.00
2. Cumulative Costs.....	562,486.00
(a) Balance.....	-0-
3. Cost Sharing.....	14,572.30

I certify that all expenditures reported (or payments requested) are for appropriate purposes and in accordance with the agreements set forth in the application and award documents.

  
Robert Mayes  
(Signed by an Authorized Official of  
the University)  
Expenditure Control Manager  
Date 11-21-74